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MATERIALS IN SPACE

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I. INTRODUCTION

This morning I intend to tell you a little about the structural materials used in the Ranger spacecraft, along with some of the criteria by which we have selected these materials. Before we do this, it will be necessary to go into what we believe today is the space environment. Afterwards, I will discuss the use of metals, inorganic compounds, and organic materials. I shall also attempt to indicate areas where development work is most urgently needed to increase our understanding of the subject.

II. THE SPACE ENVIRONMENT

On Slide I, I have attempted to summarize the best information we have today on the space environment. Environmental factors can be listed as pressure, temperature, electromagnetic radiation (or solar radiation), solid particles, such as meteoroids and micrometeorites, neutral gas (hydrogen), ions, and electrons. As far as pressure is concerned, outer space is a pretty hard vacuum in comparison with that which we are able to produce on our equipment. Note that we are talking about vacuums on the order of 10^{-11} to 10^{-14} millimeters of mercury. The lowest pressures that we have been able to achieve artificially in vacuum equipment are on the order of 10^{-9} or 10^{-10}.

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In considering temperature, it is well to keep in mind that, because of the very low pressure, we are not talking about aerodynamic heating. Temperatures are defined by the operating limits of the scientific and telemetering equipment. Control is accomplished by providing conducting paths to the outer skin and emitting or absorbing energy by use of suitable surfaces. In the case of the *Ranger*, the target control temperature is 35°C ±15°C for the telemetering electronics gear. Maximum excursions of ±100°C are permitted in certain noncritical portions of the vehicle.

As for electromagnetic radiation, the solar constant in the Earth's orbit is 2.0 calories per square centimeter per minute. This we know quite accurately. Ninety-three per cent of solar radiation falls between 0.3 and 2 microns. The former wavelength corresponds roughly with the lower limit of the ultraviolet end of the spectrum, and 2 microns is fairly well into the infrared spectrum. I'll have more to say about this later on.

We do not have time to discuss in more detail the remaining factors shown here--solid particles, neutral gas, ions, and electrons. Suffice it to say for the moment that we know far less about these than we do about the other factors, and also that the indications are that problems concerning these will not be particularly serious, at least so far as instrumented payloads to the Moon are concerned. So, bear in mind that in the balance of this talk, we are really going to consider only the factors of pressure, temperature, and in one special case, that of thermal control surfaces, electromagnetic (or solar) radiation.

III. MATERIALS USED ON THE RANGER

The weird-looking gadget you see in Slide 2 is a Ranger spacecraft. The first two flights will be launched into highly elliptical orbits to obtain data and to prove out the over-all systems.

Materials used are as follows: The upper antenna is made of aluminum alloy joined by dip-brazing to provide good electrical continuity. The upper structure is fabricated from aluminum alloy tubing. The hexagonal frame contains a combination of magnesium alloy castings and aluminum alloy tubing. The hex. boxes themselves are made from cast aluminum alloy.

The directional antenna, which you see shown in its swung-out position pointing toward the Earth, consists essentially of an aluminum alloy frame and aluminum alloy wire mesh. The antenna feed is fabricated entirely of stainless steel joined by furnace-brazing, induction-brazing, and soft-soldering. The entire feed is gold-plated to provide radio-frequency conduction. Solar panels are mounted on an aluminum alloy honeycomb structure bonded together with epoxy adhesive. This is backed up by a riveted aluminum frame.

Inside the hex. boxes is a lot of electronics gear. In this particular design the chassis are cast aluminum; other designs may call for cast magnesium. I will explain later why different materials are used for different missions. Along with these chassis, of course, a myriad of materials is used in the electronics gadgetry, such as silicon and germanium semiconductors, carbon resistors, plastics, copper wire, solder, as well as a lot of other things that are nonstructural; so we will not dwell on this subject. We will also not go into the materials used in the individual scientific experiments, the rubidium vapor magnetometer, the electrostatic analyzer, the Lyman-alpha telescope, the ion chamber, the micrometeorite detector, and the friction experiment.

One item of interest that isn't shown is the pressure vessel that holds the nitrogen for the attitude-control jets. This is fabricated from pressure-welded titanium alloy (Ti-6Al-4V) in the stabilize-annealed condition.

Now I would like to discuss the effects of the space environment on inorganic and organic materials.

IV. EFFECT OF THE SPACE ENVIRONMENT ON INORGANIC MATERIALS

We can conveniently break the inorganics into compounds and metals.

Compounds.

No particular problems are foreseen in the use of the more chemically stable oxides and other compounds, such as those of titanium, aluminum, magnesium, chromium, thorium, beryllium, silicon, and zirconium. These materials are quite stable, and no special difficulties are anticipated under the vacuum conditions of outer space. For this reason, greater usage of ceramics over plastics for insulators is indicated for future, long-lived missions. About the less chemically stable oxides and other compounds, such as those of lead, copper, nickel, cobalt, iron, and molybdenum, less is known. We are doing some thermodynamic calculations on some of these compounds at JPL, but the results are not in yet.

Metals

We feel that we have a pretty good understanding of what will happen to metals under space conditions. Behavior of pure metals can be predicted with reasonable certainty by use of the Langmuir equation. This equation seems to be quite good for computing evaporation under high vacuum conditions where mean free paths are long, so that there are essentially no atomic collisions.

Slide 3 shows the Langmuir equation expressed in two different forms. Note (equation on the left) that the pressure is equal to a constant times the rate of evaporation in gm/cm^2-sec times the square root of the temperature in degrees Kelvin divided by the molecular weight. It is important to remember, then, that for pressures lower than about 10^{-7} millimeters, evaporation rate for a given metal is a function of temperature only. Environmental pressure has nothing to do with it. On the right, I have rearranged the equation to show the rate of evaporation in centimeters per year. This is a convenient form for calculating what might happen to metals. Using the arrangement on the right, I have calculated the data plotted on the next slide.

Slide 4 shows the evaporation loss from the surface in centimeters plotted against the time in years. (Note that this is a logarithmic scale.) The horizontal lines correspond to one atom layer, one ten-thousandths of an inch, and one one-hundredth of an inch. Note that magnesium will lose one atom layer in about three years at 50°C. This is the temperature with which we are concerned in the Ranger. Obviously, for structural purposes, we are not particularly concerned with this for missions planned for the near future.

Information on this slide does, however, point up what we consider a problem. If we consider chassis, which I mentioned earlier, the evaporation of material from the chassis and subsequent deposition in other cooler areas resulting in shorting out of electronic circuits might pose a very real problem. As you can see from the slide, magnesium at 50°C would lose, and presumably redeposit on an equivalent cooler area, one atom layer in about three years. We can assume that one atom layer would be required to conduct electricity if deposition is uniform. Some of the chassis are likely to run hotter than this because of the electronic gear associated with them. Therefore, if we consider a higher temperature, say 135° C, one atom layer would be deposited in a matter of a few days. These conclusions depend, of course, on the assumption that the layer is deposited in a uniform manner. However, there is a possibility that it may be deposited as whiskers, in which case shorting may occur in times other than those which we can predict in this way. Suffice it to say that we consider this a real problem, and have taken steps to deal with it. This is why in some Ranger designs which have relatively long lives, we have used aluminum chassis. In other designs which will be in space for short periods (less than two weeks), we have used magnesium castings in order to conserve weight. They are dimensionally identical with the aluminum castings, using the same patterns.

Undoubtedly, future missions will require the lowest weight that can be achieved practically. Therefore, we are also looking at barrier coatings, such as electroplates, for inhibiting sublimating of magnesium. You will note that tin is quite stable, and would take far longer than a hundred years to sublime and redeposit one atom layer. Therefore, tin might be an excellent coating. Cadmium and zinc, which are often used as coatings, would volatilize more rapidly than does magnesium.

Slide 5 enables us to get an idea how the other metals might be expected to behave in space vacuum. The slide shows the metallic elements arranged in order of decreasing vapor pressure. You will remember from the previous slide that aluminum and tin are quite stable; so, we can say that anything near these, or below these, is going to be stable. This includes such elements as lead, silver, copper, gold, and chromium. Thus, it is obvious from the standpoint of placing barriers on magnesium that there are a number of choices which should work well.

So far we have discussed pure metals. While we know less about alloys, I think it is safe to say that the situation is not of particular concern. For instance, a 70/30 brass contains 30% zinc, which is quite volatile. It shouldn't be so bad as pure zinc, since there is considerably less of it present. In addition, you must bring zinc atoms to the surface before they are in a position to fly off into outer space. Therefore, diffusion probably becomes the controlling phenomenon here. Fortunately, most alloys,which are substitutional types, have very low diffusion rates at the relatively low temperatures we are talking about.

V. EFFECT OF THE SPACE ENVIRONMENT ON ORGANIC MATERIALS

Considerably less is known about the behavior of organic polymers. I think we can say categorically that most plastics pose problems. In my opinion, we will have to be very careful in our use of plastics for long-life missions.

One point to remember about plastics, however, is that they really don't have vapor pressure in the same sense that metals do. Degradation is thought to be a process of portions of molecules detaching and flying off.

Slide 6 summarizes some data obtained by the Wright Air Development Center. Weight losses obtained on some polymer films in a vacuum of 2×10^{-5} millimeters of mercury after exposure for 24 hours at 300°C are shown. I have arranged them in rough order of amount of weight lost. The Kel-f, silicone, cellulose acetate butyrate, styrene butadiene, as well as the phenolic and epoxy look best according to these data. Some of the materials look terrible. Polysulfide, polyurethane, and nitrocellulose certainly should be avoided even for short time usage.

Unfortunately, the investigators did not obtain the data in such a way as to provide much insight into the mechanisms of weight loss. We feel that much of the loss is caused by the boiling off of plasticizers and low-molecular-weight fractions. If such is the case, serious dimensional changes, and in some cases embrittlement, might occur. It is not difficult to visualize a poorly chosen potting compound shrinking and tearing wires loose.

Another point to remember is that frequently polymer degradation in air involves oxidation. Slide 7 shows comparative hydrogen chloride evolution at 180°C for polyvinyl chloride in oxygen, air, and nitrogen. Since there is no oxygen in outer space, we can expect some polymers to behave differently than they do in air, possibly even better.

Plastics in general are probably more susceptible to radiation damage than are inorganics. We are not particularly concerned about this at present, since our planned missions are all well beyond the Van Allen belts.

Another thing we must consider about plastics is the change that can occur as a result of ultraviolet radiation. Therefore, I have shown in Slide 8 the spectral distribution of the solar radiation against a background of the spectrum. Of particular importance is the lower wavelength end, where you can see that the Earth's atmosphere cuts out a lot of the ultraviolet. It lowers the magnitude, and it also cuts off some of the lower wavelengths. As a result, we can readily see that we will have much more ultraviolet hitting our thermal control surfaces than would be the case on Earth. Because of this, we are somewhat concerned about solar-reflecting paints, where we want as high a reflectivity as possible. Ultraviolet is well known to cause yellowing of paints, so that reflectivity would be lowered under service in space. Considerably more work needs to be done on this subject, since paints are extremely attractive from the practical standpoint.

I would like to mention one rather important, practical problem concerned with plastics, and that is that the plastics industry is not very well standardized. As a result, every plastics manufacturer has his own favorite plasticizer, dyes, and other additives, which makes it very difficult to pin down just what you really have. For this reason, we have chosen to formulate our own silicone paints so that we will know exactly what is in them.

The whole area of plastics is certainly one in which a lot more information is needed than we now have.

Unfortunately, time does not permit discussing two other very important materials areas. Lubrication is a serious problem in outer space as it is on Earth. I have only touched on the subject of thermal control, in reference to paints, but there are problems connected with other surfaces which must also be used for effective thermal control of more complex spacecraft.

VI. CONCLUSIONS

You may have gathered from the sampling I have given you that we really know very little about the subject of material behavior in space. Most of our conclusions are based on theoretical considerations. Such conclusions are no better than the assumptions that must be made in arriving at them. Some really good development and evaluation work must be done in the following areas if we are to gain confidence that our missions will have a good chance of performing as planned: (1) polymers, (2) thermal control surfaces, and (3) bearings and lubrication.

In the above three areas, the theories are entirely inadequate to predict behavior. Metals and compounds require further work also to verify the theories and assumptions we have made about them. However, I would place them on a lower priority basis than the other three areas. A certain amount of work on metal surfaces and degradation of compounds such as molybdenum and tungsten disulfide is, of course, indicated in the second and third categories.

Both laboratory experimental work and controlled flying experiments are indicated. The latter, because of expense and limited space availability on the vehicles, should be performed after conducting screening tests in the laboratory.

A word about an alternate route--that is, trial and error--is in order. Remember that these instrumented payloads are, by and large, sent out into space, never to return to Earth. In most cases it will be very difficult, or impossible, to correlate materials failures with mission failures with a satisfactory degree of certainty. Manned payloads will be little better than instrumented payloads in this respect. Materials failures will often result in an inability to return to Earth. In this case also, very little will be learned about failure causes.

Pressure	10^{-11} to 10^{-14} mm of Hg
Temperature	Dependent on vehicle requirements (for Ranger – T = 35°C ± 15°C) (maximum excursion = ± 100°C)
Electromagnetic Radiation	Solar constant ≈ 2.0 cal/cm^2–min 93% between 0.3 μ and 2 μ Black-body temperature, approximately 6000°K
"Solid" Particles	
Meteoroids (> 1mm radius)	v = 15 mi/sec d = 0.1 gm/cm^3 Flux = 2.5×10^{-12} particles/cm^2–sec
MicroMeteorites (< 1mm radius)	v = 6 mi/sec d = 0.1 gm/cm^3 Concentration = 10^{-14} to 10^{-15} particles/cm^3
Neutral Gas (hydrogen)	Concentration < 1 atom/cm^3
Ions	
Mev Range	Flux = 4 particles/cm^2–sec (bursts to 120 particles/cm^2–sec)
1 Kev to 1 Mev	Flux = 10^9 – 10^{12} particles/cm^2–sec
Thermal Ions (below 1 Mev)	(none above 60,000 mi)
Electrons	Concentration = 100 particles/cm^3 (as high as 10^6 particles/cm^3 in Val Allen Belts, 600 – 60,000 mi)

Source: Materials Problems Associated with the Thermal Control of Space Vehicles – MAB-155-M

Fig. 1. The space environment.

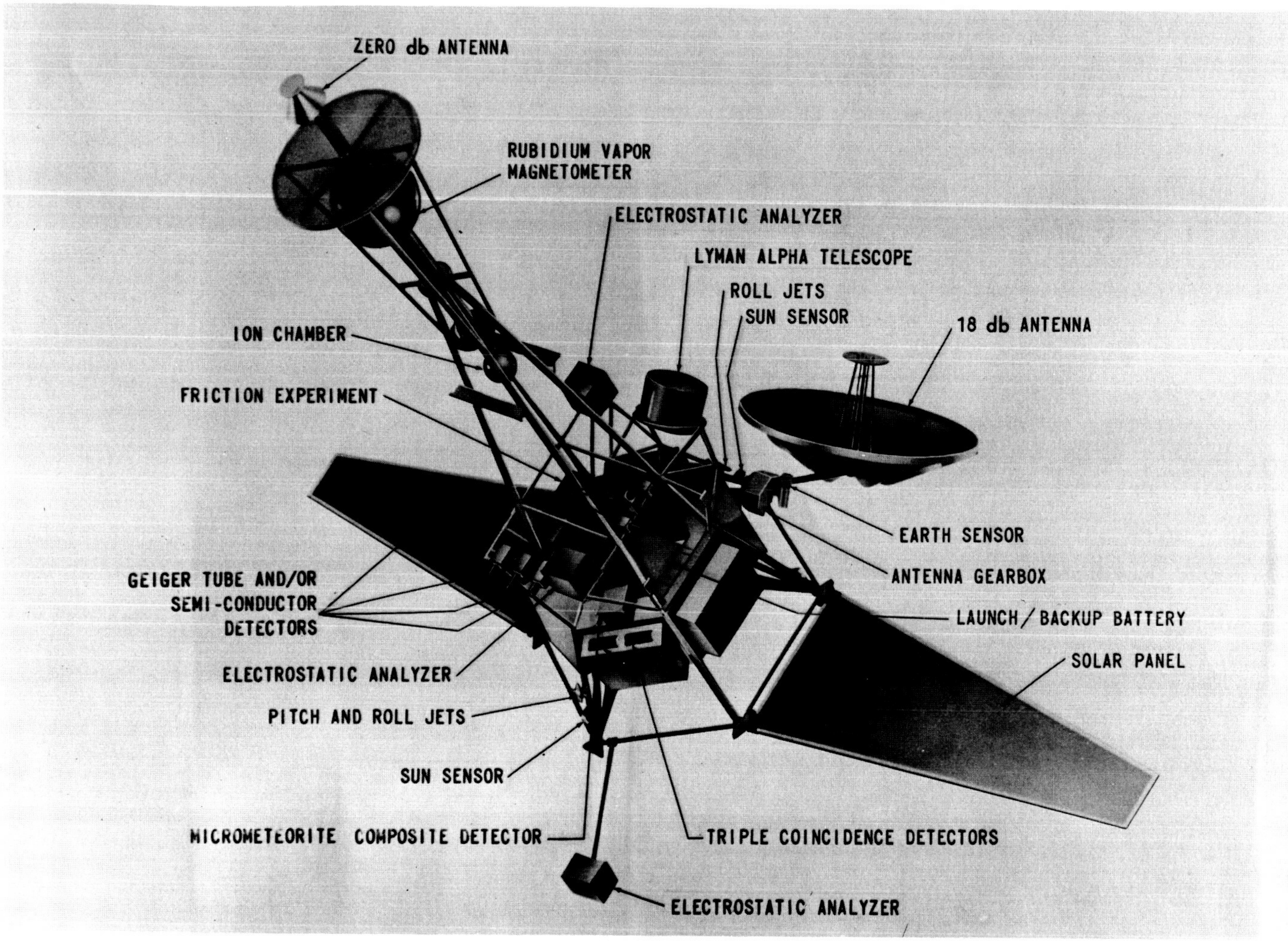

Fig. 2. Ranger spacecraft model.

$$p = K_1 w \sqrt{T/M} \qquad \text{or} \qquad R = \frac{K_2 p}{d\sqrt{T/M}}$$

p = Vapor pressure, mm. of Hg

K_1 = 17.14

w = Rate of evaporation, gm/cm^2-sec.

T = Temperature, °/K

M = Molecular weight

R = Rate of evaporation, cm/yr.

$K_2 = 1.8 \times 10^6$

d = Density, gm/cm^3

assume gaseous molecules monatomic
except
Se, Te, Sb, Bi, C, which are assumed diatomic

Fig. 3. Langmuir equation.

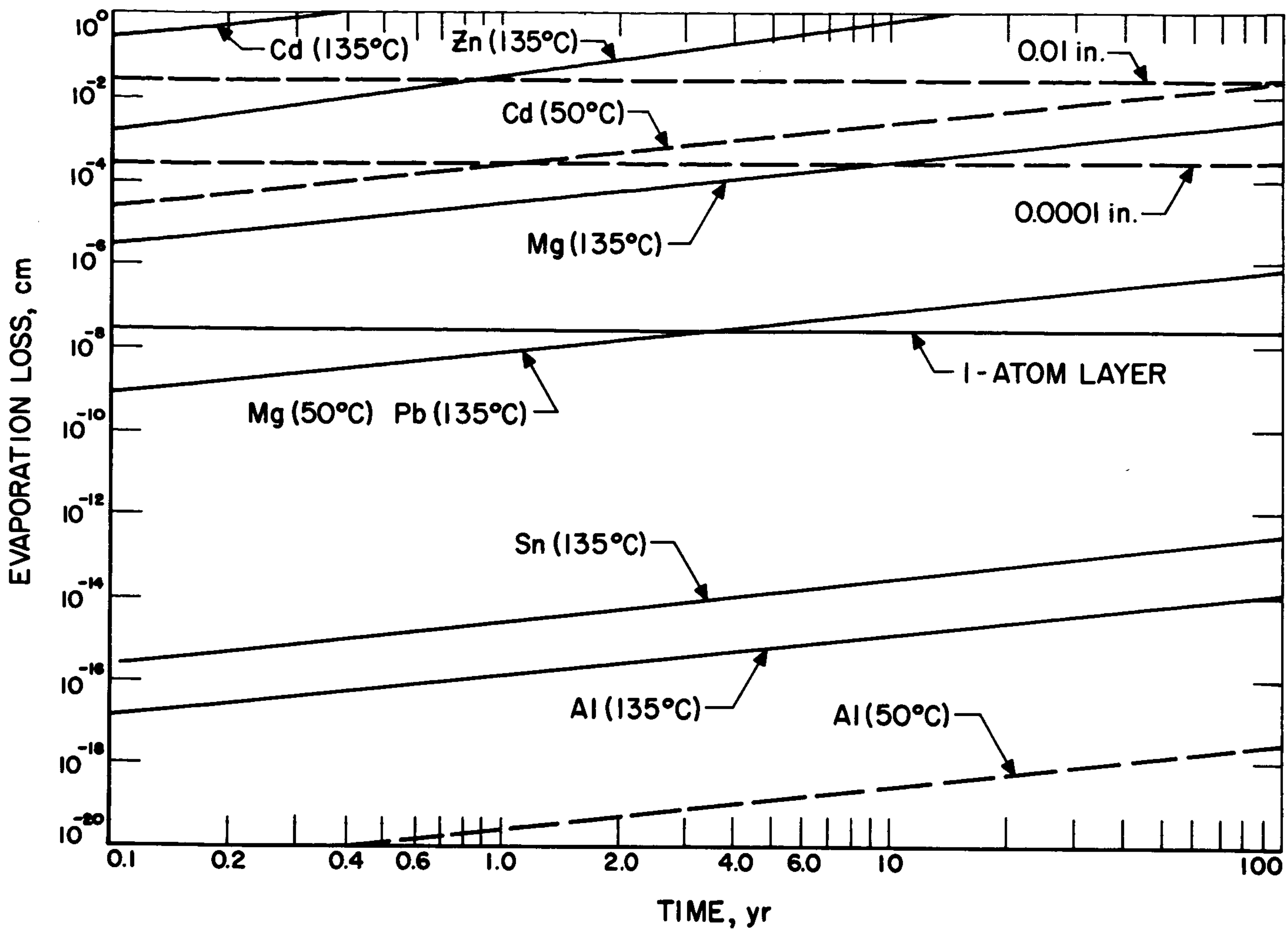

Fig. 4. Theoretical evaporation of some metals in vacuum.

Highest	Xe	Zn	Ag	Ti	
	Br	Te	Sn	U	
	I	Mg	Al	V	
	Hg	Sr	Be	Rh	
	S	Li	Cu	Pt	
	Cs	Sb	Au	B	
	Rb	Ca	Ge	Ir	
	K	Ba	Cr	Zr	
	P	Tl	Fe	Mo	
	Cd	Bi	Pd	C	
	Na	Pb	Co	Re	
	As	In	Ni	Ta	
	Po	Ga	La	W	Lowest

Fig. 5. Elements arranged in order of decreasing vapor pressure.

Polymer	% loss after 24 hr at 300°F	Polymer	% loss after 24 hr at 300°F
Kel-F	1.6- 2.2	Linseed Oil	10.5-28.6
Silicone	2.3- 6.6	Acrylic	17.5-42.8
Cellulose Acetate Butyrate	2.3-11.2	Polyester	19.7
Styrene Butadiene	2.7- 4.7	Neoprene	26.3
Phenolic	4.5	Nitrocellulose	47.2
Epoxy	7.3-28.4	Vinyl Copolymer	60.3
Polyvinyl-Butyral	8.7-41.7	Polysulfide	63.1-63.5
Alkyd	9.8-17.4	Polyurethane	66.5
Silicone-Alkyd	10.0-13.7	Nitrocellulose	82.3

Source: 1st Symposium "Surface Effects on Spacecraft Materials" Ed. by Clauss

Fig. 6. Weight losses for some organic polymer films.

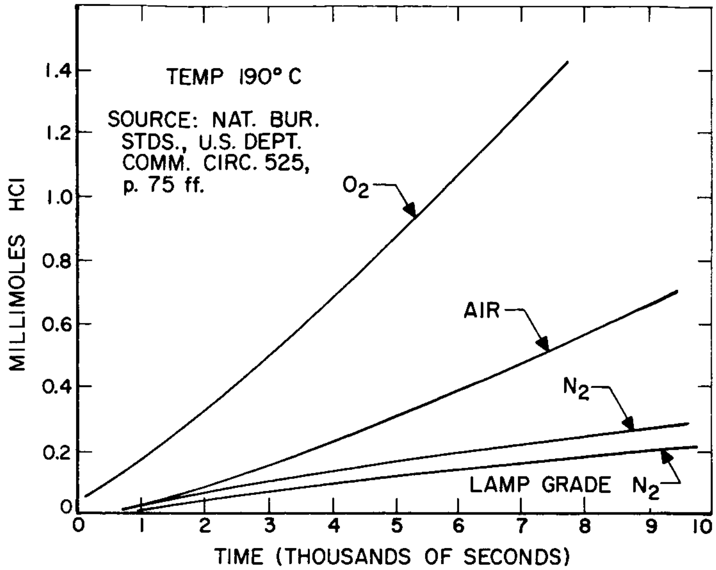

Fig. 7. Thermal decomposition of polyvinyl chloride in O_2, air, and N_2.

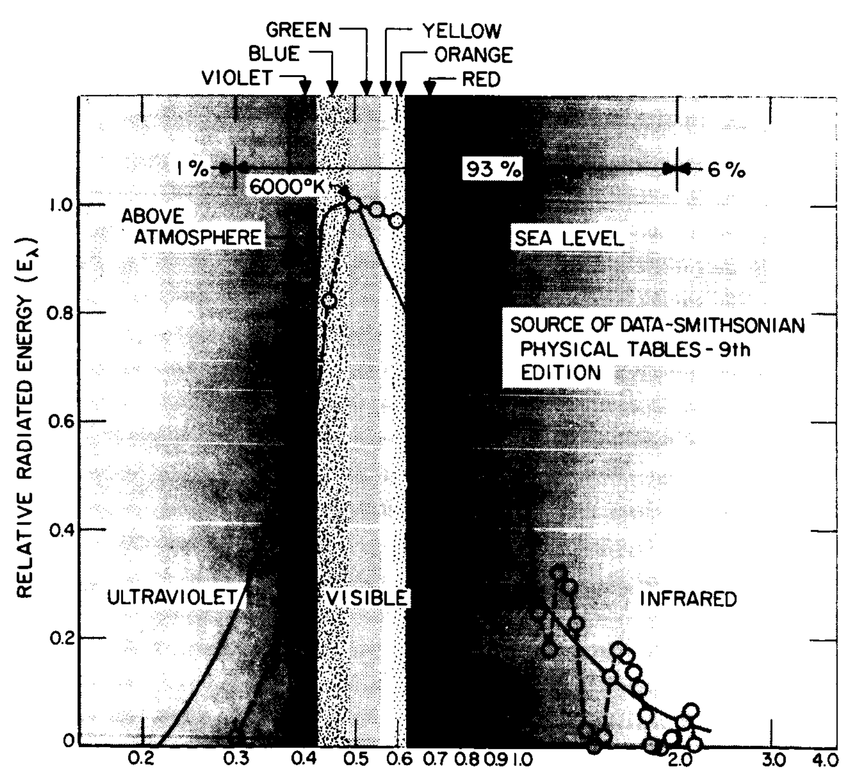

Fig. 8. Spectral distribution of solar radiation.